Chapter 1

Reciprocity Between Urban Heat Island Effect and Air Pollution

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Abstract

Heat pollution in urban environments accelerates air pollution which in turn can enhance heat pollution. In cities, solar radiation is more effectively absorbed than in rural surroundings by large, dark, man-made surfaces (streets, parking lots, airport aprons and runways, roofs, railroad yards, etc.) and stored in heat-retaining structures for delayed re-emission in the infrared (IR). These heat enhancers are called passive anthropogenic heat sources. Active anthropogenic heat sources (waste heat from air conditioning, power plant cooling towers, engines, etc.) add to the stored IR emissions from the ground. Enhanced IR emissions from the ground and convective and advective flows of air in contact with hot surfaces cause temperatures in cities to rise relative to surrounding rural areas. Collectively, these phenomena are called 'urban heat island (UHI) effect.'

Anthropogenic activity also causes chemical emissions (hydrocarbons, sulfur compounds, NO_x compounds, aerosols, etc.) in the atmosphere. Solar ultraviolet (UV) radiation dissociates and ionizes air pollutants. The resulting radicals and ions undergo chemical reactions in the atmosphere, producing many new species and enhancing naturally existing species (H_2O, CH_4, CO_2, etc.). The rates of chemical reactions with low activation energy barriers and the formation of aerosols are enhanced by rising temperatures. Many of these species, including aerosols, absorb and re-emit radiation in the IR. Thus, heat radiation is trapped by urban air and creates a positive feedback on the heat island effect and on chemical pollution. We describe the reciprocity of these effects, the sensitivity of heating rates of the local atmosphere due to anthropogenic trace gases, aerosols, and ground albedo variations, and suggest potential countermeasures.

1. Introduction and definitions

The world's rapidly increasing population poses serious problems to the climate. It is well known that the burning of fossil fuels leads to an increase of atmospheric CO_2 that, like a greenhouse, is thought to trap infrared (IR) radiation and causes a slow but steady global warming. However, anthropogenic activity has an even more immediate effect on the urban microclimate by steadily increasing temperatures in cities relative to the surrounding rural areas. The rising temperatures result either directly from human activity (active anthropogenic heat sources), such as heating of homes and work spaces and waste heat from air conditioning, engines, and cooling towers, or indirectly through changes in land use (inactive anthropogenic activity), such as pavements, buildings, and railroad yards that absorb and retain more of the Sun's light and re-emit it as heat. The urban temperature excess above rural values and attributable to anthropogenic activity is called the urban heat island (UHI) effect. The UHI is of particular concern today as cities grow into megalopolises that have a major impact on regional climate. Measurements indicate that the UHI effect is growing in cities world-wide. Thus, it may be an important contributor to the perceived global warming. While there is no doubt about the increasing amounts of CO_2 in the atmosphere, most temperature measurements are made at weather stations located at airports that are notorious heat islands. Thus, the question arises about the significance of these measurements in relation to global warming.

Rising temperatures in cities can also adversely influence air pollution. Ozone production is a major health concern. Thus, increasing population and the tendency of rapidly growing and expanding cities create a dilemma: We have the means to determine trends but the freedom to ignore predictions, we can see further than we are willing to act. Ultimately the uncontrolled expansion of cities will have to be restrained and city planning will become a major issue. Yet, now is the time to plan and deliberate the changes that an increasing population will demand. Clearly, the UHI effect is an important issue to consider.

The UHI effect is also important to demand-side power management of electric utilities. For example, a city in the south of the USA, consuming typically 800 MW of power on a moderately cool day, may need 3 GW during periods of peak demand on a hot day. On summer days, when temperatures are above 21°C, each 1°C increase requires an additional 110 MW of power. Most of the additional power is used for air conditioning. Since most of the additional power ends up as heat in the city, it contributes to the active anthropogenic heat sources.

Cars not only produce air polluting gases, but also heat. Less than 15% of the energy content of gasoline goes into moving a car: over 60% are engine losses. The rest of the energy goes into braking, driveline, rolling, standby, acre. and accessory losses. Most of the losses arc again active anthropogenic beat sources. Additionally, cars pollute the air chemically. Regulations to reduce air pollution are being enforced or encouraged by government entities, For example, in Texas, a state rich on natural gas sources, government vehicles arc being converted to use natural gas. However, decisions about the use of gasoline versus natural gas, or ethanol versus methanol as oxygen-bearing gasoline additives have not yet been made.

2. Historical sketch

2.1 The urban heat island

The fact that cities produce a heat island in the surrounding thermal environment has been observed for over a century. Garstang *et al.* (1975) reviewed work on heat islands prior to 1975 and considered four main categories for their study: statistical, energy flux balance, turbulent mixing, and dynamic models. We discuss these models briefly to place current work in its historical context. All models arc either hydrodynamic representations (advection and convection) with assumed atmospheric temperature profiles, or radiative representations with an approximation for advection. Some models include chemistry. The reader is referred to Garstang *et al.* (1975) and to Bennett and Saab (1982) for extensive reviews of heat island studies and the heat island as it pertains to pollution dispersal.

The causes for UHIs include: (1) active anthropogenic heat sources; (2) elevated heat capacity and reduced surface albedo of buildings and paving materials relative to that of rural soil; (3) reduction in surface wind Speed due to surface roughness (structures, such as buildings); and (4) reduced moisture available for evapo-transpiration. Based on modeling by Atwater (1972), Yu and Wagner (1975), Torrance and Shum (1976), and Welch *et al.* (1978), the factors in order of relative importance are: active anthropogenic beating, surface roughness, heat storage capacity, and availability of moisture. Myrup (1969) concluded that active anthropogenic beating was not an important contribution, but that it varies from city to city. It may be more important in cities where air-conditioning or heating of buildings is a large factor. Models disagree on the importance of heat retention, mainly because of the uncertainties in the value of the average heat capacity of the city surface, and because models have assumed plane parallel geometry. Terjung and Louis (1971) concluded that high-rise urban structures can absorb more than six times the radiation of rural plains. Spelman (1969) found that surface heating is more important than surface roughness, but that surface roughness becomes increasingly more important as wind speed increases above 5 m/s and a turbulent boundary layer traps heat near the ground.

An early attempt at numerical modeling of the urban heat island was that of Myrup (1969). The energy flux balance models conceived by Myrup were based on quasi-one-dimensional soil - air columns in which the net radiation at the surface and active anthropogenic heating are balanced with latent heat of vaporization, sensible heat flux into the atmosphere and soil, and possibly advection from neighboring columns. If F is the net radiative flux, then

$$F + I = H + L_e + G + \Delta A . \tag{1}$$

where H is the transfer of sensible heat, L_e the energy of evapotranspiration, G the net storage of heat, ΔA the advection of energy to the adjacent environment, and I an internal heat source. The internal (active anthropogenic) source of heat on the left side of the equation and the advection sink were neglected in Myrup's (1969) model. The fluxes of latent heat and sensible heat were treated in terms of diffusion equations. The net radiative flux was given in terms of the solar flux at a given latitude (with the solar declination and hour angle as variables), the mean atmospheric transmission, and mean surface albedo. The latent heat flux is parameterized in terms of the relative humidity, which was interpreted as a function of the fraction of the total area occupied by transpiring plants. The vertical distributions of wind speed, temperature, and specific humidity were assumed to vary logarithmically. All calculations were made for clear skies and no consideration was given to active anthropogenic sources of heat, such as combustion. In spite of the simplifications, the results were both qualitatively and quantitatively reasonable. Myrup concluded that a 20% green area is a critical value needed to mitigate the UHI effect.

Differences among models arise because of differences in estimated heat capacity of the urban soil and surface, estimates of the available moisture and relative humidity, and treatment of advection. The effect of humidity and its relationship on evaporative flux was examined by Adebayo (1991).

Radiative transfer models differ in complexity. Yoshida and Kunitomo (1986) included radiative heating of the atmosphere by gases (H_2O, CO_2, O_3) and aerosols and considered active anthropogenic heat sources. They investigated the effects of ground albedo, ac:N'C' anthropogenic heat release, ground emittance, evaporation, surface roughness thermal diffusivity and heat capacity of the ground, and size (Distributions of aerosols. They conclude that an increase in all parameters increases the surface temperature of urban areas by night. In the daytime the surface roughness and aerosols decrease surface temperature in urban areas. Consistent with Ibis. Balling and Brazel (1986) found from measurements that the nighttime temperature in Phoenix at 02:00 1,S'1' increased by an average of about 4.5°C from 1948 to 1984 and June's nighttime temperature rose by more than 5.5°C. Radiative models predict larger differences between urban and rural areas in winter and at night than in summer and in the daytime, respectively.

2.2 Air pollution as it applies to the urban heat island effect

Gaseous and aerosol pollutants are largely ignored in UHI studies but were recently shown to be important in energy flux balance models. Also, in all energy flux balance models known to the authors, clouds are ignored. Olfe and Lee (1971) justified neglecting radiative cooling by pollutants by citing Atwater's calculations, concluding that elevated inversions would only provide substantial cooling if their residence times were long. For a mean velocity of 3 m/s, the residence time of's pollutant over a city is about an hour; therefore radiative cooling is important only for stagnant conditions. Radiative heating and cooling by pollutants is important for major urban centers with basins, such as Los Angeles and Mexico City.

Atwater (1971) showed that urban pollution produces an elevated inversion that acts to inhibit the escape of pollutants. He used transmission functions for aerosols computed from Mie theory at a wavelength $\lambda = 0.483$ µm, and a concentration of particles observed over Minneapolis. The models for IR transmission of the atmosphere assumed only water vapor and carbon dioxide. Since the surface temperature was pre-specified, the aerosols could only change the vertical temperature structure. Because the model neglects advection, it is strictly realistic for nonadvective, stable cases, which occur most often at night. The strongest effects occur for calm conditions. Infrared radiation by the polluted layer leads to an intensification of the heat island by night, but attenuation of solar radiation weakens the heat island during the day. Air pollution effects also weaken the wind, leading to an intensification of pollution concentration. Subsequent work on the radiative effects of pollution by Bergstrom and Viskanta (1973) and Zdunkowski *et al.* (1976) show that IR from the heated aerosol layer will increase the heat island in the early morning, but the reflection of solar radiation by the aerosol layer will decrease the magnitude of the heal island by day, The relative effects of heating in the 1 R and cooling in the visible are sensitive to the optical properties of the pollutants. More recent work by Bennett and Saab (1982) concentrates on pollutant dispersal.

in addition to aerosol pollutants. gaseous pollutants produce important radiative forcing [Gurney *et al.* (1988)]. Changes in tropospheric ozone mixing can produce positive radiative forcing comparable in magnitude to that caused by other greenhouse gases [Lacis *et al.* (1990)]. The increase in tropospheric ozone is believed to be caused by increases in precursor molecules, such as ('O, NO_x and hydrocarbons, which also tire pollutants. The vertical distribution of ozone is available for the stratosphere from satellites, but for the troposphere it is only available from ozone-sonde data.

The effect of pollutants on the surface temperature will depend on their absorption and scattering properties. '1'0 the extent that the pollutants absorb and scatter visible radiation, the daytime surface temperature will be decreased relative to that with cleat skies. However, at night, IR radiation by the polluted layer may act to increase the urban surface temperature relative to that in the surrounding rural environment. Thermal radiation by pollutants may lead to an intensification of the UHI by as much as 50% in the early morning hours [Venkatram and Viskanta (1976)].

Brazel *et al.* (1988) analyzed a long-term database of smoke and haze formation in the rapidly growing city of Phoenix, Arizona. They found no change in the frequency and intensity of smoke and haze conditions with population increase, but a significant increase in duration of such events when they compared the period from 1949 to 1966 with the period from 1967 to 1985. From the analysis of the data they concluded that the increased smoke and haze duration is related to the impact the growing UHI has on the structure of the local inversion layers. They suggested a link between urban-i induced temperature and wind changes and air quality levels in rapidly growing metropolitan areas.

3. Relevance to climate change

As discussed by Garstang *et al.* (1975), cities begin to exert a major mo dification on airflow in the boundary layer as they grow into megalopolises. Major urban megalopolises such as Los Angeles and the eastern seaboard of the USA already exert major regional influences. The radiative forcing due to ozone, which is decreasing in the stratosphere and increasing in the lower troposphere because of urban air pollution, is already comparable to increases in other greenhouse gases [Wang *et al.* (1993)]. Thus, the effects of urban air pollution are global in extent.

Measurements indicate that the UHI effects and the amounts of CO_2 in the atmosphere are increasing world-wide. While there is no doubt about the increasing amounts of CO_2, most temperature measurements are made at airport weather stations. However, airports are notorious heat islands. Thus, predictions of global warming based on temperature measurements must be viewed with great care.

Charlson *et al.* (1992) found that tropospheric aerosols and in particular anthropogenic sulfate aerosols contribute substantially to radiative forcing, Short-wavelength solar radiation and modification of short-wave reflective properties of clouds by sulfate aerosol particles increase planetary albedo, thereby exerting a cooling, influence on the planet. The globally averaged climate forcing due to anthropogenic sulfate is estimated to be -1 to -2 W/m^2. This perturbation is comparable in magnitude to current anthropogenic greenhouse gas forcing but opposite in sign. Thus, the aerosol forcing has likely offset global greenhouse warming to a substantial degree. However, differences in geographical and seasonal distributions of these forcings preclude any simple compensation. Aerosol effects must be taken into account in evaluating anthropogenic influences on the climate and in formulating policy regarding controls on emission of greenhouse gases and sulfur dioxide. Resolution of such policy issues requires integrated research on the magnitude and geographical distribution of aerosol climate forcing and on the controlling chemical and physical processes.

4. Measurements of heat pollution

The main techniques that have been used to measure the urban heat excess are temperature comparisons from urban and rural meteorological stations, the auto-traverse method, and remote sensing by aircraft and satellites in the thermal infrared. The problem with using meteorological data to quantify the UHI effect is to determine whether the local measurements are representative of the entire area and to correct for altitude differences of the weather stations. Because the auto-traverse method is confined to roads, the temperature measurements are representative of the sub-rooftop level, which will be cooler than the satellite-derived temperatures. In addition, it may take several hours to traverse a city by car, so that temporal corrections are required. Both HCMM (Heat Capacity Mapping Mission) and AVHRR (Advanced Very High Resolution Radiometer) data have been employed in studies of the UHI by Henry *et al.* (1989) and Gallo *et al.* (1993), respectively. The AV111<1{ data have a spatial resolution of 1.1 km at nadir, compared with 600 m for the i ICMM. 1 Ienry *et al.* claim that the increased spatial resolution and overpass times of the I ICMM, early afternoon for low-latitude sites, make this data more useful for heat island studies than AV1 IRR.] Ienry *et al.* concluded that although the auto-traverse, AV111<1<, and HCMM techniques produced similar patterns, the absolute values of the measured heat island varied widely. In one example, tile pre-dawn value of the heat island derived from the satellite data was 9°C, while that from the auto-traverse method was 3°C. These differences may be a result of measurements at di fferent dates and times, although the meteorological conditions, in particular wind speed, were similar. 1 Ienry *et al.* attribute the difference to the height at which measurements arc obtained: the auto traverse method measures sub-rooftop temperatures, whereas the satellite data arc representative of the radiatively active surface that may be al or above tile rooftop.

The results of Gallo *('/ al.* (1993) she\\'c(i that the amount of variation in ΔT_{min} (urban T_{min} minus rural T_{min}) explained by the satellite data, either in terms of surface temperature or vegetation index, was only 22% for all weather stations or 440/0 for weather stations exhibiting less than 500 m elevation difference. Although those cities with the greatest contrast in green vegetation be tween urban and rural environments had the greatest contrast in ΔT_{min} there was much scatter in the data when ΔT_{min} (measured at weather stations) was plotted against $\Delta T_{surface}$ (measured by tile satellite). However, Garstang *et al.* (1975) point out that significantly different urban heat excesses may be measured for the same locale on di fferent days for which meteorological conditions arc similar. A similar study was carried out by Caselles *et al.* (1991) using ground temperature measurements and NOAA satellite data. The study of the effects of urban air pollution on the atmospheric heat budget has implications for our understanding of both weather (i.e. short-term local effects) and climate (long-term global effects).

5. Models

5.1 Statistical models

Many early attempts to describe the UHI phenomenon were statistical. Statistical models indicate the sensitivity of the heat island to various parameters, not necessarily those physically responsible for the underlying cause. For example, Sundborg (1950) related the strength of the heat island to cloudiness, wind speed, temperature, and water vapor pressure. The regression parameters for his fit differed for night and dav solutions. ( )k c (1 973) parameterized the urban - rural temperature di fference in term s of city size Ludwig and Kealoha (1968) relate the magnitude of a UH II to both city size and upwind rural lapse rate; and Summers (1905) relates potential temperature difference to city size. heat released from the city surface, air density, and upwind rural wind speed. He showed that the maximum heat island effect as a function of city size was di fferent for North American and European cities, indicating that other parameters, such as passive and active anthropogenic beat generation, were responsible. Oke and Hannell (1970) suggested that the critical value of the wind sped above which the beat island will not form is given by

$$U_{crit} = 3.4 \log P - 11.6, \qquad (2)$$

where P is population and U is velocity in m/s. Sbca and Auer (1978) derived a linear dependence between heat island intensity and wind speed.

5.2 Energy flux balance

For convenience, solar and terrestrial radiation are separated at a wavelength $\lambda \approx 4$ µm, into the short-wave and the long-wave portions of the spectrum. in the shml-wave portion, the source is tbc direct solar radiation and scattering is important by gases, clouds, and aerosols. In the long-wave region, the sources are thermal radiation from the surface and isotropic IR emission from the atmosphere. Rayleigh scattering is neglected, only first-order scattering by aerosols and cloud particles is important in the IR. The IR radiation is trapped by air and pollutants. particularly by aerosols, which may form an inversion layer over a city. The surface (ground plus structures) boundary condition is determined from the power balance of solar radiation reaching the surface, conduction into the surface, heat storage below the surface, anti rc-emission from the Sill'face. The coefficients for albedo, IR emissivity, heat capacity, and conduction play a major role in this determination. Parameterized standard values of active anthropogenic heat sources have' to be added to the boundary conditions.

Solar UV radiation dissociates and ionizes atmospheric constituents and pollutants, creating many highly reactive species with absorption and emi ssion bands in the IR region of the spectrum. For example, all hydrocarbons absorb and emit in the $\lambda \approx .3.4$ µm spectral region because of their C-H stretch bonds. The CH_2 and CH_3 (information bonds absorb and emit at $\lambda \approx 7.1$ µm. While water vapor (humidity) inhibits the transfer of

1 R radiation, several pollutants and in particular aerosols block the high transmission 'windows' left open between the water absorption bands. Thus chemical pollutants and aerosols in temperature inversion layers can be very effective additional sources in trapping I R radiation.

1 n general, for radiative flux calculat ions, the atmosphere is assumed to be horizontally homogeneous. With this assumption, the heating rate is related to the vertical gradient of the flux

$$dT(z)/dt = [g/c_p] \text{ 111''(2) /(11'(2)} , \qquad (.3)$$

whew $T(z)$ is the temperature at height z, g the Earth's gravitational constant, c_p the heat capacity at constant pressure, $P(z)$ the local pressure, and $F(z) = F^{\uparrow}(z) - F^{\downarrow}(z)$ the net radiative flux. The net flux is the sum of the net short-wave and the net long-wave fluxes, which are calculated separately. Heating occurs because of absorption of short-wave radiation, while cooling occurs because of the divergence of the net long-wave radiation. in radiative s(cady-state, the averaged flux divergence is zero. However, heat may be convected or carried by latent heat of vaporization, and a complete mode] must include these terms.

in the visible, because both Rayleigh scattering and scattering by aerosols and clou ds are important, the radiation transfer must include multiple scattering. One method developed and thoroughly tested is the discrete ordinates method, i.e. an n-stream approximation [Stamnes *et al.* (1988) Tsay *et al.* (1990)]. The physical processes include thermal emission, scattering, absorption, and bi-directional reflection at the lower boundary. Active anthro pogenic heat sources may be included as well. For computational efficiency, parameterization of gaseous absorption is required when calculating radiation transfer including scattering. One such method is exponential sum fitting of' transmissions. It approximates transmission functions of a given spectral region by a finite sum of exponential terms

$$T_B(u) = \sum w_i \exp(-b_i u) \quad . \qquad (4)$$

where T_B is the band transmission, u the absorber amount (column mass per unit area), b_i the equivalent absorption coefficient (cross section per unit mass) in the ith wavenumber interval, and w_i the w'eight of the ith interval [Tsay *et al.* (1990)]. This method is also employed for the band model of water vapor lines in the IR. Because the exponential terms behave exactly like monochromatic optical depths, they are easily incorporated into multiple scattering schemes, although pseudo-grcy continuum absorption coefficients must be included to treat the overlap from absorbing, gases.

The sets Of coefficients, b, and w_i, for gaseous transmission by H_2O, CO_2, O_3, and O_2 have been obtained by fitting the LOWTRAN [low-resolution transmission Kneizys *et al.* (1988)] functions with 20 cm^{-1} spectral intervals [Wiscomb (1977) Slingo and Schrecker (1982) Wiscomb and Evans (1985)']. Narrow-band models (resolution < 100 cm^{-1}) and other broad-band models (resolution > 100 cm^{-1}) are available. High-resolution absorption coefficients are available in the HITRAN database, but line-by-line calculations are usually not carried out. Low-resolution models have been compared with high-resolution line-by-line computations for the ICRCCM project (World Meteorological Organization, 1984). Some low-resolution models compared favorably with line-by-line results for standard models. The solar spectrum measured by Labs and Neckel (1968) and Neckel and Labs (1984) is often used for input.

The most important atmospheric radiators for IR cooling are water vapor, carbon dioxide, and ozone. Oxygen is a minor absorber. Because spectral line-by-line calculations are computer intensive, computations are generally carried out with parameterized models. However, in the presence of clouds or aerosols, the IR flux is influenced by scattering as well as gaseous transmittance. For the IR, only first-order scattering must be considered. The model of Ellingson and Serafino (1984) can be used to compute correction terms for first-order scattering by aerosols of given optical depth for partly cloudy or hazy atmospheres and the model of Ellingson and Gille (1978) can be used for clear sky flux calculations. The net flux may be obtained by summing relatively few bands. Parameterizations currently used in the General Circulation Models (GMCs) are those of Chou (1984) for the transmittance of water vapor, Chou and Peng (1983) for carbon dioxide, and Rodgers (1968) for ozone. The water vapor continuum from the far wings of spectral lines and from water dimers was parameterized by Chou and Arking (1980, 1981).

Flux calculations in the IR are straightforward for clear atmospheres, because the source is simply the Planck blackbody radiation, $B_\nu(T)$, and Rayleigh scattering can be neglected. The monochromatic flux is

$$F_\nu(\tau) = 2\pi\, B_\nu(T_s)\, E_3(\tau_0-\tau) + 2\pi \int_{\tau_0}^{\tau} B_\nu[T(\tau')]\, E_2\,(\tau'-\tau)\, d\tau' \quad , \qquad (5)$$

where E_2 and E_3 are the second and third exponential integrals, respectively. However, in the presence of clouds and aerosols, the IR flux is influenced by scattering and gaseous transmittance.

With the addition of aerosols or clouds, the net flux into the surface troposphere region can either increase or decrease, depending on the aerosol properties and their vertical profile. For nonconservative scattering, the surface always loses some solar flux. Although the long-wave effect of aerosols is expected to be only about 30% of that in the visible, it may be significant. Ellingson and Serafino (1984) concluded that the rate of temperature rise due to Saharan aerosols was $dT/dt \approx 1$ °C/day for a 123 mb layer containing most of the aerosols, comparable to the clear tropical sky heating, due to water vapor absorption of 0.5 km. Radiative heating rates for aerosols may be less than 0.2°C/day at the same time forcing convective heating, rates twice as great, accompanied by changes in vertical velocities (Ramaswamy, 1988). Because there is some cancellation between radiative cooling and convective heating, it is important to consider convective heat transfer as well. The radiative - convective response may be evaluated by parameterizing the convective response as a diffusive process [Ramaswamy and Kiehl (1985)]. in general, dynamical cooling due to uplift is small and can be neglected. The effect of the hydrological cycle is obviously important in the tropics. but need not necessarily be considered for mid-latitude urban sites. Moisture related effects can only be properly considered with three-dimensional models.

The effect of clouds on radiative transfer is an active area of current research. Recently it has been shown that the transfer of visible radiation through clouds depends on small-scale structure within the clouds. This irregularity can be handled by stochastic radiative transfer methods [Evans, (1993) Malvagi *et al.* (1993)], however, these approaches are very computer intensive. A parameterization of multiple scattering through a partly cloudy atmosphere is being attempted by Malvagi *et al.* (1993). The effect of broken cloudiness on IR radiative transfer has been studied by Killen and Ellingson (1994).

Aerosols are often characterized by their radiative properties as water soluble, soot, sulfuric, dust-like, and maritime. or as urban. continental, and maritime. The single-scattering albedo and asymmetry parameters of these had categories have been studied by various researchers [Carlson and Caverly (1977) Carlson and Benjamin (1980) Rao *et al.* (1988) Ackerman (1988)]. Single scattering albedos and asymmetry parameters for desert aerosols are given by Longtin (1988). Volcanic and arctic, aerosols have been extensively studied because of their potentially large impact on climate. Maritime aerosols are routinely mapped by the AVHRR satellite, and desert aerosols were studied during the MONEX campaign. However, urban and continental aerosols are not retrieved by Earth-orbiting satellites because the ground albedo under the optical path is unknown, whereas the albedo of the oceans is well-known and does not change with seasons. Ice and snow covered regions are also avoided for satellite retrieval because of problems over areas with high ground albedo and confusion between snow cover and cloud cover.

5.3 Turbulent mixing

Partitioning of the radiative surplus or deficit between the soil and air depends on the level of turbulent activity, and the partitioning of turbulent transport of heat to the air between the sensible and latent forms depends on the availability of moisture. The ratio of heat transport between the sensible and latent forms is called Bowen's ratio, β. Typical rural values of β are in the range 0.4 to 0.8. If the surface is wet and the evaporation is at the potential rate, the value of β is about 0.3, but β may be 1.5 or greater for dry conditions. Moisture availability is therefore the primary criterion in determining the type of heat transport. Advection may increase transport by latent heat above the potential rate. On the other hand, paved areas, buildings, and deserts are characterized by a lack of latent heat flux. In the 'urban canyon' composed of a paved surface with buildings on two sides, the turbulent transport of heat into the air is almost entirely by sensible heat. When turbulence is suppressed, the heating can be described as the divergence of the radiative flux

$$\partial T/\partial t = (1/\rho c_p)\cdot\partial F/\partial z \quad . \tag{6}$$

This sometimes holds at night, especially in a stagnant urban canyon. In general, however, turbulence is enhanced over cities because of the large-scale roughness.

In the presence of turbulence, the variation of potential temperature, θ, with height can be described by a conservation equation

$$d\theta/dt = \partial\theta/\partial t + \mathbf{v}\cdot\nabla\theta = \partial(K_H\partial\theta/\partial z)/\partial z + \textstyle\sum_i S_i \quad , \tag{7}$$

where $K_H\partial\theta/\partial z$ is the flux of sensible heat, the eddy diffusivity, K_H, is commonly derived from mixing length theory, and the S_i are other sources such as latent heat, radiant, and active anthropogenic sources. The diffusivity can also be derived from turbulent transfer models or by consideration of local stability. Apparently the choice of diffusivity profile, $K_H(z)$, is not critical to determining the profile of potential temperature.

The prediction of surface temperature is obtained by considering the energy rate (power) balance between visible plus atmospheric radiation flux plus artificial heat sources at the surface, and reradiation from the ground plus latent and sensible heat fluxes (similar to eq. 1)

$$(1 - \alpha)\cdot F_s + F_{IR} + I = \sigma\theta_o^4 + L\rho K_q(\partial q/\partial z)_+ + \rho c_p K_H(\partial\theta/\partial z)_+$$

$$+ C_S K_S(\partial T/\partial z)_- \qquad (8)$$

where the subscripts + and - mean that the gradient is evaluated above and below the surface, respectively. The other, previously undefined, symbols mean: K_S, the heat diffusively coefficient of the soil; K_q, the diffusivity coefficient for humidity; K_H, the heat diffusivity for the atmosphere; L, the latent heat of water; C_S, the heat capacity of the soil; $\partial q/\partial z$, the humidity gradient; α the ground albedo; F_s, the visible, incident radiation flux; F_{IR}, the IR radiation flux at the surface; and I, internal (active anthropogenic) heat sources.

5.4 Dynamical Models

Dynamical models solve the equations for the flow and temperature perturbations around a heat island using conservation of mass, momentum, and energy, the equation of state, the Navier-Stokes equation for the motion, and thermodynamics. Typically, diabatic heating is introduced at the surface [cf. Olfe and Lee (1971)]. Dynamic models generally solve the advection - diffusion equations using finite difference schemes, although simplified models have been solved analytically [cf. Baik (1992)]. These models assume that the differences between urban and rural net radiation are negligible, and that heat transfer is solely through sensible heat flux. Olfe and Lee (1971) assumed that the surface temperature perturbation was prescribed by a sinusoidal function; in addition to using a sinusoidal heating function Richiardone and Brusasca (1989) used an empirical form of the horizontal healing function. Forcing may be introduced [cf. Richiardone and Brusasca (1989)] by means of a buoyancy flux, $B(x,z,t)$, related to tile sensible heat flux by

$$B(x,z,t) = H(x,z,t)/(\theta\rho c_p) \qquad (9)$$

The thermodynamic potential temperature perturbation, $\theta(x,z,t)$, is written in terms of a buoyancy flux

$$db/dt + N^2\cdot w = -dB/dz\ , \qquad (10)$$

where

$$b = g\cdot[\theta(x,z,t) - \theta(x,z,0)]/\theta(x,0,0) = dp'/dz\ . \qquad (11)$$

$H(x,0,t)$ is the heat flux at the ground at time, t, p' the perturbation pressure, N the Brunt-Vaisala frequency, w the vertical wind speed, and g the Earth's gravitational constant. The sensible heat is assumed to be separable of the form

$$}/(.Y,Z./)' \ \gamma\ A(t)\, B(x)\, C(z,t)\ . \tag{12}$$

where $C(z,t)$ decreases from a value of 1 at the ground to zero at the top, and is derived from

$$H(x,0,t)\ \Delta t/(\rho c_p) = \Sigma_j\, \Delta 0_j\ \Delta z\ . \tag{13}$$

The potential temperature curve near the ground is computed in a way that forces constant potential temperature to height, z. Then the heating above level z must satisfy

$$\Sigma\ \Delta 0_j\ /\ \Sigma\ \Delta 0_i = C(k-1, \Delta z, t)\ . \tag{14}$$

Baik (1992) solved an equivalent thermodynamic energy equation by introducing a heating function, q, given by

$$q(x,z) = q_0\, f(x)\ g(z)\ , \tag{15}$$

where q_0 is the amplitude of the healing function, $f(x)$ is a Gaussian function, and $g(z)$ is a linearly decreasing function of z.

his equivalent thermodynamic equation is given in terms of potential temperature perturbation, O. as

$$(/0/(/! + N^2 w/g = 0_0\, g/(c_p\, T_0)\ , \tag{16}$$

where T_0 is the basic state temperature.

Richiardone and Brusasca (1989) concluded that the atmospheric stability ant] the ratio between urban and rural sensible beat fluxes at the ground are the most important factors influencing urban circulation, kinetic energy production, and heal island intensity.

Results show a convective cell centered on the heat island with subsidence in the surrounding country with potential temperature anom alies following the city outline. When winds are included in the mode] [Baik (1992)] the dynamical models show that the region of upward motion is displaced downwind of the heat island with downward motion over the beat island itself. The displaced convection cell enhances precipitation downwind of the heat island. Baik's model was able to produce bands of positive and negative velocity perturbations, descending motion over the heat island and ascending motion on the downstream side.

In more realistic models, heat is transported from the surface to the atmosphere by turbulent thermal diffusion processes. Models including detailed boundary-layer physics are the three-dimensional mesoscale model of Hjelmfelt (1982) simulating the effects of the city on boundary-layer airflow, and the two-dimensional mesoscale model of Byun (1987) simulating the urban mixed layer. Tso *et al.* (1991) showed that by introducing simplifying assumptions in the surface energy balance equation, an analytic solution could be found. Analytical solutions are faster and simpler than numerical solutions and can often provide greater insight into the problem. They found that their analytical results for surface temperature were within 2.30/0 of numerical results, the difference in magnitude being only about 0.5°C at the maximum.

5.5 Chemical air pollution models

In addition to normal atmospheric constituents (N_2, O_2, CO_2, H_2O) and inert gases, urban air contains many pollutants that come from high-temperature combustion reactions and other anthropogenic sources. Photolytic and gas-phase reactions transform these species further into a plethora of atmospheric constituents. Solar radiation drives much of the nonequilibrium chemistry of the atmosphere through photochemically initiated processes. In the daytime, these photolytic reactions are very important in forming highly reactive radicals. The consequences of the photochemical changes are ultimately decided by the relative rates of competing chemical kinetic reactions, many of which are very sensitive to the air temperature. Most current models consider atmospheric chemistry as a function of solar zenith angle and the *mean* air temperature. An interesting connection is the investigation of pollution chemistry as a function of temperature variations about the mean temperature and the long-range effects of rising mean temperature as indicated by the UHI effect.

We approached this problem in a three-stage effort. In the first phase, we compiled the database for the reaction network from several literature sources combined with data from our group. Special attention was paid to temperature dependence and the coefficients, A, B, and C in the Arrhenius equation of the gas-phase chemical rate coefficients

$$k = A\cdot(T/300)^{B}\cdot\exp(-C/T) \ . \qquad (17)$$

Table 1 gives the ratio of the rate coefficients at $T = 318$ K to those at $T = 278$ K for a few sample reactions. In the second phase, our chemical kinetics computer code was adapted to the problem at hand. This involved primarily the addition of an advection term. The adapted code was validated by comparing results with other models at a specific mean temperature. In the third phase, we investigated the *relative* effects of temperature variations on the concentrations of pollutants using temperature-dependent rate coefficients.

Table 1. Arrhenius coefficients for selected temperature-dependent reactions

Reaction[1]		A	C	k_{318}/k_{278}	Ref.
1. $OH + CO$	$\rightarrow CO_2 + H$	2.2×10^{-13}	80	1.04	a
2. $OH + H_2CO$	$\rightarrow HCO + H_2O$	3.0×10^{-11}	250	1.12	a
3. $NO_2 + NO_3$	$\rightarrow NO + NO_2 + O_2$	2.5×10^{-14}	1230	1.74	b
4. $HO_2NO_2 + M$	$\rightarrow HO_2 + NO_2 + M$	$1.3\times10^{[illegible]}$	10418	112.	b
5. $N_2O_5 + M$	$\rightarrow NO_2 + NO_3 + M$	1.6×10^{14}	10655	124.	b
6. $O(^3P) + CH_3CHO$	$\rightarrow CH_3CO + OH$	1.2×10^{-11}	986	1.56	b
7. $CH_3CO_3NO_2$	$\rightarrow CH_3CO_3 + NO_2$	$1.9\times10^{[illegible]}$	13543	458.	b
8. $CH_3O + O_2$	$\rightarrow HCHO + HO_2$	1.0×10^{-13}	1300	1.80	b
9. $OH + CHF_2Cl$	$\rightarrow$ Products	1.2×10^{-10}	1650	2.11	c
10. $OH + CH_2F_2$	$\rightarrow$ Products	7.8×10^{-13}	1300	1.80	c

[a] Prasad and Huntress (1980)
[b] Atkinson and Lloyd (1984)
[c] Nelson *et al.* (1993)

In these reactions M indicates a catalyst which can be any neutral air molecule. The investigation of the effects of temperature variations on urban air pollutants yields two important results: (1) Changes of the rate coefficients for many air reactions throughout the range $278 < T < 318$ K show large variations, e.g. reaction 8 changes by a factor of 1.80, reaction 4 by a factor of 112, and reaction 5 by a factor of 124. (2) The investigation of the *relative* effects of temperature variations on the concentrations of atmospheric pollutants has shown that temperature variations are significant in the atmospheric chemistry of urban environments, particularly for the important minor constituent, ozone. In

[1] M is any neutral air molecule. The coefficient B in the Arrhenius equation is zero for the reactions listed here. Reaction 7 (peroxyacetyl nitrate, or PAN) dissociates thermally.

the USA, the Environmental Protection Agency (EPA) has established air cleanliness guidelines for ozone concentrations. At 80×10^{-9} parts of ozone in city air an ozone advisory is issued with suggestions for curbing the buildup of ozone. If 120×10^{-9} parts of ozone are reached, an alert is issued. If an urban area has four ozone alerts in a three-year period, it is labeled a non-attainment city and the EPA enforces strict air quality controls.

Some important rate coefficients for the production and destruction of ozone are presented in Fig. 1. Ozone concentration increases by about 6% for a diurnal temperature increase of 10°C. This small relative change means that interpretations of the absolute measurements of ozone concentrations must be normalized with respect to the air temperature.

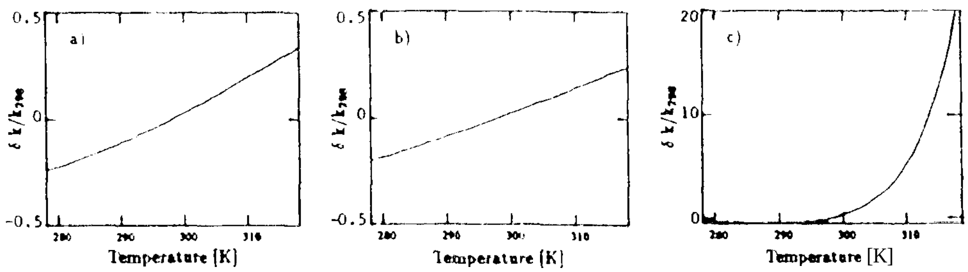

Figure 1: Change of rate coefficients relative to 298 K (the usually assumed mean temperature) through the temperature range 278 - 318 K, for the reactions (a) $CH_3O + O_2 \rightarrow HCHO + HO_2$, (b) $O(^3P) + CH_3CHO \rightarrow CH_3CO + OH$, and (c) $N_2O_5 + M \rightarrow NO_2 + NO_3 + M$.

Ozone chemistry in the troposphere:

Production:	$NO_2 + h\nu \rightarrow O + NO$	($\lambda \leq 400$ nm)
	$O + O_2 + M \rightarrow O_3 + M$	
	$OH + CO \rightarrow H + CO_2$	
	$H + O_2 + M \rightarrow HO_2 + M$	
	$HO_2 + NO \rightarrow OH + NO_2$	

Net:	$CO + 2O_2 + h\nu \rightarrow CO_2 + O_3$	($\lambda \leq 400$ nm)
Destruction:	$O_3 + h\nu \rightarrow O(^1D) + O_2(^1\Delta_g)$	($\lambda \leq 310$ nm)
	$O(^1D) + H_2O \rightarrow OH + OH$	
	$HO_2 + O_3 \rightarrow OH + 2O_2$	
	$OH + CO \rightarrow H + CO_2$	
	$H + O_2 + M \rightarrow HO_2 + M$	

Net:	$CO + O_3 + h\nu \rightarrow CO_2 + O_2$	($\lambda \leq 310$ nm)

The more UV ($\lambda \leq 310$ nm) is blocked, the less O_3 is *destroyed.*

5.6 Combined hydrodynamic, radiation, and chemical model

The UHI dome is a volume of air with a height of a few hundred meters over a city. in the case of Phoenix, Arizona, for example. the Salt River Project (SRP) used a variety of methods to monitor the long-term heat island effects. They included a network of ground-based sensors. which are real-time weather monitoring stations that communicate by microwave. and *in situ* measurements from aircraft and weather balloons for determining vertical profiles over the city and surrounding desert (a three-dimensional database). In the summer of 1990, the Southwest Area Monsoon Program was conducted. It consisted of P-3 aircraft carrying meteorological instruments that collected data over the Phoenix area. Remote sensing was also used by SRP. High-resolution IR satellite images obtained by NOAA were incorporated into the ground-based and *in situ* database. However. (difficulties arose in correlating the IR 'skin' temperature from the satellite images with meteorological quantities (see also Sect. 4 above).

To evaluate databases describing such heat island domes, a three-dimensional, time-dependent model is needed for the temperature profile above the city and the air flow around the city. Energy balance models alone cannot account for advection and mixing, momentum transfer or wind velocity perturbations. Purely dynamic models cannot investigate the radiative effects on chemistry and the IR trapping of radiation by pollutants and aerosols. Therefore, dynamical considerations must be coupled with radiative energy balance. Such a model must simulate the transport of visible solar radiation through the atmosphere, its reflection and absorption on the ground, the conduction and storage of heat in the ground, the emission of IR radiation from the ground (including active and passive anthropogenic sources), and the IR radiative transfer through the atmosphere including the heating of the atmosphere. It must also include advective and convective dynamics and allow for feedback of increasing urban temperatures on chemical reactions that produce smog, ozone, and other air pollutants. It must include state-of-the-art radiative transfer and analytical and numerical solutions to the equations of dynamics and thermodynamics. The effects of clouds and humidity must be included. Figure 2 schematically presents such a model.

While air pollutants and aerosols have no direct influence on advection and convection (since they are only minor constituents of the atmosphere), they can trap IR radiation which increases the air temperature. The temperature profile with altitude depends on convection and radiative heating, both in turn depend on the temperature gradient. IR radiation trapping is particularly effective when an inversion layer exists. The increase in air temperature enhances chemical reactions, producing more air pollution. This reinforcing cycle will not continue *ad infinitum*, eventually conditions will be reached where the inversion layer is destroyed. Predicting convective break-through of the inversion layer is extremely difficult.

The surface (ground plus structures) boundary condition is determined from the power balance of solar radiation reaching the surface, conduction into the surface, heat storage below the surface, and re-emission from the surface. The coefficients for albedo, IR emissivity, heat capacity, and conduction play a major role in this determination. Parameterized values of active anthropogenic heat sources are added to the boundary conditions. The boundary condition calculation can be treated as an independent problem with input (solar radiation) and output (heat and reflected radiation). The heat dome model can be used to compare the effects of changing anthropogenic boundary conditions and thus becomes a tool for potential counter measures or UHI and air pollution.

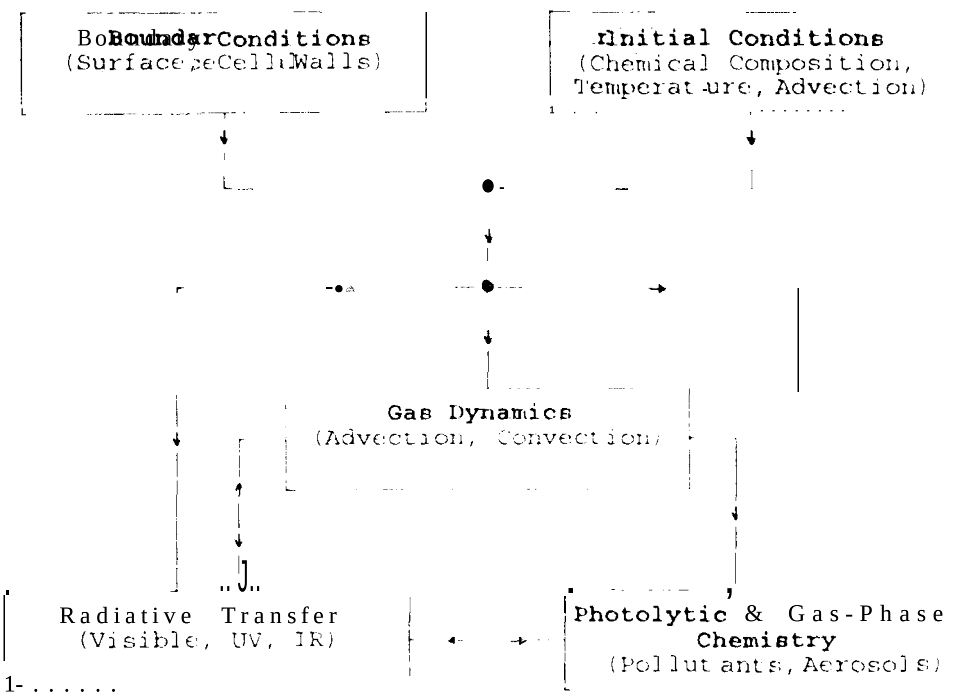

Figure 2: Time-Dependent, Multi-Dimensional Urban Heat Island Model

6. Urban planning

Much can be done to reduce the UHI effect. Inactive anthropogenic heat sources can be reduced by increasing the surface albedo, i.e. the ratio of reflected to incident sunlight. Light-reflecting roofs are particularly effective. h4c(litcrr:l)lca11-style buildings use light colors to reflect sunlight. over-hanging roofs shield walls and reflect more sunlight back into space. Also streets and parking lots can be built to be less heat absorbing. Multi-leveled parking garages reduce the fraction of sunlit surface area per parking space. Airports are notorious heat islands. Aprons, runways, and roofs of buildings should be light in color. Areas between runways should not be paved with black. heat absorbing materials. Railroad cars can be fitted with light-reflecting roofs.

Improved insulation of surfaces reduces heat conduction into the interior of structures or into the ground. When combined with materials of reduced heat capacity, storage of heat can be greatly reduced. Heat storage is the main factor of increased minimum temperatures at night, which is a major contributor to the increasing heat island effect. increasing the area of radiating surfaces also reduces heat storage. Overhanging roofs and shaped surfaces that conduct heat from a sun-exposed side to a shady side can be very effective in reducing the UHI effect.

Expansion of a city perpendicular to the direction of predominant winds readily permits heat and chemical air pollution to be dispersed. Industrial zones should be built on the down wind side of a city. Large, rapidly expanding cities should take advantage of terrain and consist of a main city with well-separated satellite communities. The satellite cities can be connected with rapid-transit systems through zones of vegetation to allow for the cooling effects of evapo-transpiration.

7. '1'epics of future research

Areas that need more work are the modeling of surface roughness, heat capacity, and relative humidity of cities, estimating passive and active anthropogenic heat sources, and including cff.eels of clouds, pollutants, and aerosols in radiative transfer. Energy flux balance models alone cannot account for advection and mixing, momentum transfer. m wind velocity perturbations. The increase in air conditioning in the southwest of the USA since the time of Myrup's (1969) study justifies a re-evaluation of his results that internal (active anthropogenic) heat sources are unimportant. Spelman (1969) found that surface heating is more important than surface roughness, but that surface roughness becomes increasingly more important as the wind sped increases above 5 m/s. Radiative effects 01' urban pollutants will introduce cooling by day and heating by night and will change the form of the heating function as assumed by Richiardone and Brusasca (1989), for example. Because an increase in aerosols could ca use cooling or heating of the surface and of the earth - atmosphere system, we believe that this is an area that is ripe for further investigation. For this purpose, absorption and scattering characteristics of aerosols have been studied recently [cf. Ohta *et al.* (1990) Goodwin and Mitchner (1986) Andreyev (1987) Hitzenberger and Rizzi (1986)].

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